Nanoenabled Directions for N/MEMS

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DARPA MTO

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# Report Documentation Page

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Nanotechnology Enabled Opportunities

- Chip-Scale Microfluidic Analyzers
- Nanosensors
- Nanowires for Sensors and Electronics
Two key themes:

- Nanotechnology enables new applications and drives performance
- Nanotechnology is emerging as a key aspect of integrated microsystems
N/MEMS Program Examples

Micro Gas Analyzers
- CNT Preconcentrators
- Nanomechanical Sensors
- CNT Detectors
- Functionalized Chemiresistors

N/MEMS S&T Fundamentals
- CNT Sensors
- NEMS Biosensors
- Nanoresonators
- Reconfigurable Nanoelectronics

Micro Cryogenic Coolers
- Thermal nanostructures
- Nanoenabled cryogenic cooling

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Objective:
Enable remote detection of chemical agents via tiny, ultra-low power, fast, high sensitivity, chip-scale gas analyzers with low incidence of false positives.
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Integrated N/MEMS Components

- Very high effective surface area
- Chemical functionalization
- DRIE
- Chemical polishing
- Low proff-mass
- Chemical functionalization
Enhancement of Performance

Gain ~ 10,000

FID signal, pA

Time, sec

TOL, C-12, DMMP, DEMP, DIMP, DCH

H2O

75 mV bias
7 ag SF₆ pulses

CO₂: (1.0 ± 0.3) Hz/fg
SF₆: (0.9 ± 0.3) Hz/fg

7 ag SF₆ pulses

Added Mass (ag)

CO₂: (1.0 ± 0.3) Hz/fg
SF₆: (0.9 ± 0.3) Hz/fg

1 Hz/fg slope

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Nanotechnology Benefits:

- Nanotechnology and MEMS (a terrific combination!)
  - Size: 40,500 cm³ → 2 cm³
  - Nanotechnology enables systems with unprecedented performance:
    - Sensitivity: 1 ppb → < 1 ppt
    - Analysis time: 15 min → 4 s
    - Energy per analysis: 10⁴ J → 1 J

Nanotechnology Lessons Learned:

- Micro Gas Analyzers (MGA) Program
- Possible Multiplexing
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**N/MEMS S&T Fundamentals**

- **Goal:**
  - Support basic research of importance to DoD in N/MEMS

- **Technical Challenges**
  - Failure Mechanisms and physics
  - New materials and processes
  - Scaling laws in multiple domains
  - Interfaces and interconnects between the macro-micro-nano worlds.

**MEMS/NEMS**
- Surfaces & Interfaces
- Reliability Physics
- Scaling Physics
- Materials & Processes
- Interconnections
- Noise Mechanisms
- Modeling
- Signal Processing

**Applications**
- Microfluidics
- Data Storage
- Biology & Medicine
- Biotechnology
- rf Comms
- Optical Comms
- Chemical Sensing
- Navigation
- Uncooled IR
- Displays

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MEMS/NEMS
- Surfaces
- Interfaces
- Reliability
- Scaling
- Materials
- Fabrication
- Modeling
- Nanostructures

Microfluidic Processors
UC Irvine
Biosensors
Harvard
Functionalized Surfaces
Cornell
Nano Probes
Caltech
Self-Configuring ICs
Carnegie Mellon
RF Scaling
UC Berkeley
Reliability Physics
UC San Diego
Non-lithographic Fabrication
MIT
Materials Interfaces
Stanford
Nanowire Sensors
Colorado
500 nm
Multi-Physics Modeling
Illinois
STI
BOX
Metallization Layers
Silicon substrate
A
B

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Six Nanoenabled Opportunities

1. Nanoenabled Electronics
2. Nanoenabled Informatics
3. Nanoenabled Biotechnology
4. Nanoenabled Plasmonics and Photonics
5. Nanoenabled Sensors
6. Nanoenabled Energy
Nanowire Electronics

Nanotube gate

Key Challenges
- Controlled Growth
- Selective Placement
- Interconnections

Self-Configuring Electronics

Nanotube gate

T. Schlesinger, DARPA N/MEMS S&T Fundamentals, CMU.
Self-Configuring ICs

- NEMS Thermal Actuators
- Designed-in stress gradient
- 3 µm post, 230 nm tip area

Imagine… Dynamically changing the basic function of an electronic chip according to current need.
Storage Media

Feature size reductions dramatically increase the capacity of storage media. Nanotechnology enables future optical and magnetic storage.

Nanomechanical Memory

A probe cantilever array in the IBM Millipede.

Key Aspects
- MEMS probes used for media read/write
- 3 Tbits/inch² demonstrated

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Nanoenabled Biotechnology

**Medical Therapeutics / Drug Delivery**
Therapeutic nanoparticles can be targeted to specific biological sites.

*Imagine… Site specific targeting of nerves with therapeutic nanoparticles that enhance sensory perception.*
**Plasmonics**

- Control of EM-field Enhancement
- Materials properties

**SERS Nanosensors**

Basic physics and materials science associated with SERS nanoparticles as physical, chemical, and biological nanosensors

- Spectral finger-printing
  - sub-ppt sensitivity
  - $P_D > 99.99\%$
  - FAR $< 1:10^9$
  - Fast response $< 1\text{ s}$

**Imagine...** Nanosensors with ppq sensitivities and no false alarms.

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Nanowire Sensors

- **Nanowires**, CNTs, nanocantilevers, nanoparticles, quantum dots, nanoporous, magnetic materials

Nanomechanical Sensors

- Application examples:
  - Gas sensing
  - Protein/DNA detection
  - Particle detection
  - Chemical detection
  - Signal amplification (e.g. SPR)

*Imagine… Integrated multi-functional nanosensor modules capable of multiplexed bioanalysis and physical sensing.*

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Imagine... Never having to replace a battery.

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**Goal:**
- Develop new chemical, and biological nanosensors based on nanowires

**Applications**
- All types of sensing
- Energy harvesting
- Thermal management
- New class of nanosensors for the detection of biochemical warfare agents.
Lessons Learned

What are the opportunities for nanotechnology?

1. Largest opportunities for nanotechnology are in enabling new systems

2. Look to nanotechnology to enable performance; not drive down cost.

3. Nanotechnology apps are best driven from top-down not bottom-up.

4. Multi-domain scaling is the key to performance-driven nanotechnology.

5. World competition is intense. Success in nanotechnology requires a vision, patience, and entrepreneurial spirit.
Many, many new challenges remain (Challenge = Opportunity)

**Microfluidic Analyzers**
- Preparation (nanostructures)
- Preconcentration (nanochem)
- Nanoanalytics
- Nanodetectors (multiplexing)

**SERS Nanosensors**
- Enhancement Factor (EM)
- Substrates
- Geometries
- Porous nanoparticles

**Nanowires**
- Nanosensors
- Nanosolar cells
- Nanoenergy scavenging
- Thermal interfaces